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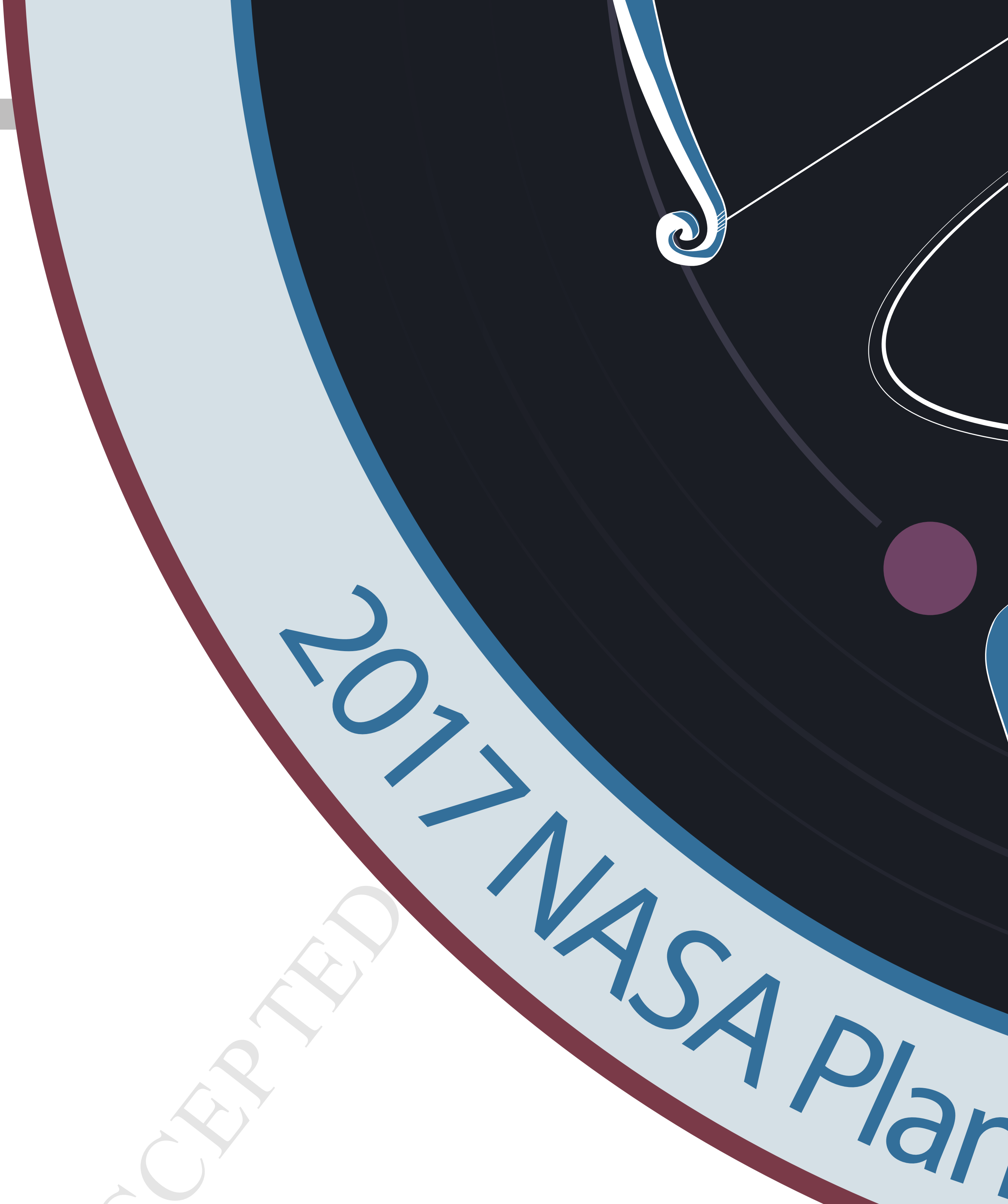
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Camilla: A Centaur reconnaissance and impact mission concept

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Abstract

Centaurs, minor planets with a semi-major axis between the orbits of Jupiter and Neptune (5–30 AU), are thought to be among the most diverse small bodies in the solar system. These important targets for future missions may have recently been Kuiper Belt Objects (KBOs), which are thought to be chemically and physically primitive remnants of the early solar system. While the Kuiper Belt spans distances of 30 to 50 AU, making direct observations difficult, Centaurs' proximity to the Earth and Sun make them more accessible targets for robotic missions. Thus, we outline a mission concept designed to reconnoiter 10199 Chariklo, the largest Centaur and smallest ringed body yet discovered. Named for a legendary Centaur tamer, the conceptual Camilla mission is designed to fit under the cost cap of the National Aeronautics and Space Administration (NASA) New Frontiers program, leveraging a conservative payload to support a foundational scientific investigation to these primitive bodies. Specifically, the single flyby encounter utilizes a combined high-resolution camera/VIS-IR mapping spectrometer, a sub-mm point spectrometer, and a UV mapping spectrometer. In addition, the mission concept utilizes a kinetic impactor, which would provide the first opportunity to sample the composition of potentially primitive subsurface material beyond Saturn, thus providing key insights into solar system origins. Such a flyby of the Chariklo system would provide a linchpin in the understanding of small body composition, evolution, and transport of materials in the solar system.

46 **Keywords:** Centaur, 10199 Chariklo, mission concept, Kuiper Belt Object, small bodies, rings

1. Introduction

Approximately once per decade, the National Research Council (NRC) Space Studies Board (SSB) synthesizes the current body of planetary science literature, community feedback, and contributed research to identify the highest-priority outstanding questions in planetary science. The National Aeronautics and Space Administration (NASA) Science Mission Directorate (SMD) develops key strategic planning for planetary science programs and, in part, selects new planetary exploration missions for funding based on the recommendations of this "decadal survey". The current Planetary Science Decadal Survey, Vision and Voyages for Planetary Sciences in the Decade 2013-2022 (National Research Council, 2011), identifies ten priority questions (PQs), each attributed to one of three crosscutting themes: building new worlds (PQs 1-3), planetary habitats (PQs 4-6), and workings of solar systems (PQs 7-10).

The robotic reconnaissance of Centaurs addresses each theme identified in the decadal survey, and are discussed in Chs. 3 and 4 of that work (NRC, 2011). However, Centaurs have not been selected as the primary target of a past, current, or future robotic exploration mission (e.g., as part of the New Frontiers or Flagship mission portfolios). Here, we define Centaurs as minor planets with a semi-major orbital axis between the orbits of Jupiter and Neptune (5–30 AU). For simplicity, we exclude predicted orbital lifetime as a qualifying criterion.

It is generally accepted that Centaurs originate from the Trans Neptunian Region and evolve towards the zone of Jupiter Family Comets (e.g. Di Sisto and Brunini, 2007). With possible origin as Kuiper Belt Objects (KBOs) (Tegler et al., 2008; Peixinho et al., 2012; Luu and Jewitt, 1996; Stern and Campins, 1996), Centaurs are likely chemically and physically primitive in nature, exhibiting cometary behavior (e.g. Luu and Jewitt, 1990) as they follow dynamically evolving orbital trajectories (e.g. Stern and Campins, 1996). We present a Centaur Reconnaissance mission concept to help resolve the origin, evolution, and state of these bodies through direct spacecraft observation, constraining our understanding of the formation and evolution of the solar system. This mission concept would address five of the PQs outlined in the decadal survey that span all three crosscutting themes.

This design effort was conducted through the NASA Planetary Science Summer Seminar (PSSS), an annual opportunity for postdoctoral researchers, early career professionals, and advanced graduate students to construct a robotic planetary exploration mission concept. Our team consisted of 18 participants and two mentors from institutions across the United States. We developed a mission concept responsive to *Vision and Voyages* and consistent with the constraints and guidelines of the SMD's Announcement of Opportunity 4 (NFAO4) for the New Frontiers Program (2016). Ten weeks of science definition, mission development and selection culminated in an intensive, weeklong effort at the NASA Jet Propulsion Laboratory (JPL), where our team worked closely with the concurrent mission design and formulation team TeamX to mature this concept for internal review. While actually not solicited in the NFAO4 (NASA, 2016), we explore a Centaur reconnaissance mission concept because of the rich opportunity for science return identified in the decadal survey, and relevance to future solicitations for robotic mission proposals.

We outline a mission concept for a flyby of 10199 Chariklo that would constrain the origin of Chariklo's double ring system, explore past and potential active surface processes, and utilize an impactor experiment to take measurements of subsurface material composition. Chariklo, the largest known Centaur with dimensions of ~330 × 265 × 170 km, is comparable in size to large main belt asteroids and features one of only a few known ring systems outside of the gas giant systems (Braga-Ribas et al., 2014; Ortiz et al., 2015, 2017) (Figure 1). In Section 2, we describe the overall science goals of the mission concept as impetus for selecting Chariklo. In Section 3, we address key mission, science, and instrument requirements. In Section 4, we outline the New Frontiers class mission concept, and spacecraft design and configuration. In Section 5, we briefly explore an alternate architecture for a lower-cost Discovery class mission concept.

2. Scientific Relevance

2.1. Motivation

The inferred relationship between Centaurs and Kuiper Belt Objects (KBOs) has motivated extensive ground- and space-based observations of these bodies. While the Kuiper Belt spans distances of 30 to 50 AU (Gladman et al., 2001; Jewitt, 1999), and is thus difficult to access, the Centaur population is typically between 5 and 30 AU (JPL Solar System Dynamics, 2017). Thought to be chemically and physically primitive remnants of the early solar system, KBOs are key to answering primary questions about the formation and early evolution of solar system bodies (Luu and Jewitt, 2002). KBOs exhibit a bimodal distribution in color for the spectrum ranging from redder than the sun to less red, or “bluer” than the sun (B-R color) that is also present, albeit broader, in observations of Centaurs (Tegler et al., 2008; Peixinho et al., 2012; Luu and Jewitt, 1996; Pike et al., 2017). Researchers have thus inferred that the Kuiper Belt is the Centaur source population, in the same way that it is postulated to be the source of the Trojan asteroids (Emery et al., 2015; Wong and Brown, 2016). These B-R colors span a range from much redder than the sun (nearly as red as Mars) (Cruikshank et al., 1998) to neutral or slightly bluer than the sun, and the source of this color distribution continues to be a subject of debate. It is noteworthy that B-R Centaur color corresponds to albedo, with the neutral/bluer group corresponding to comet-like albedos (Tegler et al., 2008; Bauer et al., 2013).

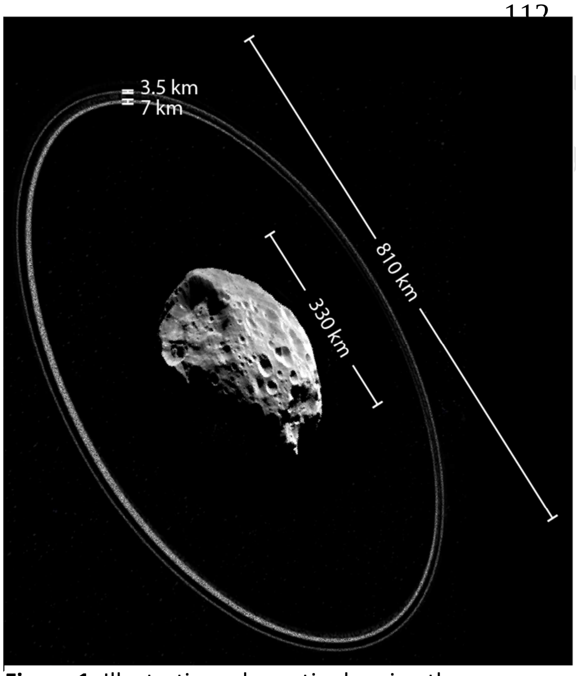

Figure 1. Illustrative schematic showing the encounter approach geometry of the 10199 Chariklo system, including the 330 x 265 x 170 km body represented by Saturn’s moon Phoebe, a proposed captured Centaur (e.g. Brown, 2000), a 3.5 km wide outer ring, a 9 km gap, and a high-albedo, 7 km wide inner ring.

As they migrate inward from the Kuiper Belt, Centaurs evolve to produce cometary tails, or comae (Luu and Jewitt, 1996; Bauer et al., 2003; Epifani et al., 2006), form ring systems (Braga-Ribas et al., 2014; Ortiz et al., 2015), and originate as—or evolve into—binary systems (Noll et al., 2006; Grundy et al., 2007). These comae can be produced at distances from the sun of ~9-16 AU (Campins et al., 1994), which is much greater than the < 3 AU typically required for coma activity in ordinary comets (Combi et al., 2004). Observations suggest the presence of more exotic ice species (Meech and Svoren, 2004) that sublimate at lower temperatures, as expected for objects formed in the far outer solar system. In addition to cometary activity, Centaurs are predicted to have short-lived orbits with half-lives of only 0.5-32 Myr (Horner et al., 2004), eventually resulting in capture by Jupiter, injection back into the Kuiper Belt, or ejection from the solar system. The cometary activity and dynamical evolution of Centaurs have led to the hypothesis that Centaurs might be one dynamical source population for Jupiter family comets (JFCs) (Volk and Malhotra, 2008; Horner et al., 2004) even though this relationship remains to be demonstrated through direct observation, for example via chemical markers.

The lifespan of Centaur ring systems (10s kyr) is predicted to be much shorter than Centaurs' typical dynamical lifespan (1s Myr) (Pan and Wu, 2016), and there are several theories for how these ring systems might form or be sustained following migration out of the Kuiper Belt. Ejecta from cometary activity, from collisions between binary bodies, from collisions with other bodies, or material produced by the tidal disruption of nearby bodies, may be captured to feed ring systems (Hyodo et al., 2016; Melita et al., 2017; Pan and Wu, 2016). However, rings are not observed on comets, perhaps due to their weak and irregular gravitational fields. Shepherd moons, binary twins, or large pieces of material formed alongside the ring, may stabilize ring systems through time and prevent their decay within the lifespan of the body (Braga-Ribas et al., 2014). The study of dynamically forming, transient rings may provide a unique laboratory for understanding the evolution of large planetary rings in the outer solar system.

Thus, Centaurs exist at the nexus of each crosscutting theme defined in the Decadal Survey (NRC, 2011). Their study may link the furthest known, most primitive small bodies in the solar system with those that most closely encounter the sun, and may inform the process of ring formation and evolution for the giant planets.

2.2. Science Goals

This Centaur Reconnaissance mission concept, Camilla, is named for the subject of Italian Renaissance painter Sandro Botticelli's 1482 masterpiece depicting a huntress taming a Centaur (though this character was later interpreted as the Titan Pallas). The mission concept is motivated by three high-level science goals (SGs) that address the unique scientific opportunities for Centaur observations. The Priority Questions outlined by the Planetary Science Decadal Survey (NRC, 2011) addressed by each of the mission concept science goals are outlined in Table 1 (a complete Science Traceability Matrix is shown in Supplementary Figure S1).

All three SGs address Priority Questions (PQs) 1 and 10, respectively "What were the initial stages, conditions and processes of solar system formation and the nature of the interstellar

Table 1: High-level Science Goals (SGs) and the Priority Questions they address, from Vision and Voyages for Planetary Sciences in the Decade 2013-2022 (NRC, 2011, Table 3.1, p. 71)

Science Goal		Priority Questions Addressed
SG1	Determine if exogenic processes dominate the current geologic state of Centaur surfaces, including spectral and morphologic characteristic	1, 4, 10
SG2	Investigate the formation mechanisms and lifecycle of complex Centaur systems (rings, coma, and binary objects)	1, 3, 4, 10
SG3	Characterize surface and subsurface chemistry to constrain the origin of Centaurs within the solar system	1, 3, 4, 10

matter that was incorporated?" and "How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?" (NRC, 2011). The Kuiper Belt is an inferred reservoir of chemically and physically primitive objects thought to form in the early stages of accretion, and is the likeliest source population for Centaurs (Peixinho et al., 2012; Tegler et al., 2008; Luu and Jewitt, 1996), and this hypothesis can be validated through spacecraft observation (SG3). If Centaurs indeed originated as primitive Kuiper Belt Objects, studying how their surface geology and chemistry evolve together and modify surface color and spectral characteristics (SG1) would illuminate the endo- and exogenic processes that dominated the surface evolution of the earliest bodies in the newly forming solar system. Similarly, understanding how these bodies may dynamically evolve as they travel inward through the solar system (SG2) has implications for volatile transport and interactions with other solar system bodies.

Each Science Goal also addresses PQ 4, "What were the primordial sources of organic matter, and where does organic synthesis continue today?" One explanation for the color of Centaurs is that redder surfaces result from the irradiation processing of organic tholins on the surface (Cruikshank et al., 1998), while the blue and neutral colors may be that of the pristine subsurface (West, 1991). However, many hypotheses for this distribution exist. Thus, the mission concept would leverage observations of the surface and subsurface chemistry (SG3) and geological mapping to infer the endo- and exogenic processes modifying the surface (SG1, 2) to test for a link between surface processes, chemical composition, and surface color. By testing the relationship between geology, color, and chemistry, this experiment will differentiate between hypotheses of the dominant sources of color variation. These processes may further serve as an analog to those taking place on other primitive bodies in the early solar system (e.g. KBOs).

Finally, Science Goals 2 and 3 address PQ3, "What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?". Constraining the origin of Centaurs (SG3) and material transport processes on the surface (SG2) may inform how primitive bodies might lose volatiles, including water, as they migrate inward through the solar system.

2.3. Target Selection

We explored two mission architectures: a multi-body tour and a single body flyby (Table 2). First, we considered a tour of multiple Centaur bodies with different spectral properties and colors that fully address SG1. However, of the 428 Centaurs in in the JPL Small-Body Database (JPL Solar System Dynamics, 2017), only 48 have a diameter > 1 km, and of those only a handful of trajectories fall within the launch windows of the NFAO4 (and anticipated NFAO5). We investigated a representative tour that included flybys of 2013 BZ55 and 31824 Elatus (10-50 km diameter), and a rendezvous at 2014 EV22 (10-15 km diameter) at 1.6 AU. While such a mission is possible, the risk to scientific return is significant because the size, shape, and color of these bodies are poorly constrained. Coma activity is observed for Centaurs at distances from the sun of > 6 AU, including significant CO outgassing (e.g. Epifani et al., 2006; Wierzchos et al., 2017). Therefore, the closer proximity of 2014 EV22 to the sun (1.6 AU) may have caused the loss of primitive volatiles over depths of a few meters or tens of meters, preventing their measurement through remote sensing. In all, no multi-body trajectory was found that could include a Centaur with a ring, coma, or companion body, eliminating the possibility of addressing SG2. However, the planned ground-based Thirty-Meter Telescope (Skidmore and

Table 2: Summary of best launch opportunities for the mission concept architectures considered. The values were calculated assuming a dry-mass of 1461 kg, except for Tour III (1315kg to fit on an Atlas V 551), an ISP of 225 for the propulsion system, and nominal C3 and ΔV (no contingency). High altitude gravity assists near Venus (V), Earth (E) and Jupiter (J) (>1000km E,V and > 3000km for Jupiter) and powered deep space maneuvers (DSM) were included to reduce the required launch Delta-V.

Mission	Launch	Launch Vehicle	Assists	Flight Time [yrs]	*C3* [km^2/s^2]	Wet Mass [kg]	ΔV [km/s]
Chariklo (**flyby**)	09/2026	Atlas V 401	V-DSM-E-E-J	12.3	12	1752	0.4
	07/2026	Atlas V 401	V-E-E-J	11.7	16	1674	0.3
	01/2030	Delta IV Heavy	J	9.9	85	1530	0.1
Chiron (**flyby**)	09/2026	Atlas V 401	E-V-E-E-J	11.9	12	1600	0.2
Thereus (**rendezvous**)	01/2026	SLS block 1	E-DSM-E-J	10.2	28	8032	3.8
Tour I (**flyby** of 2002 AO148, **rendezvous** w/ 2007 HE4)	09/2026	Delta IV (H)	E-V-E-E-J	7.5 - 11.1	12	7541	3.6
Tour II (**flybys** of 2013 BZ55, Elatus, **rendezvous** w/ 2014 EV22)	10/2025	Delta IV Heavy	E-DSM-V-DSM-E-DSM-E-J	7.7-12.9	10	7986	3.7
	08/2024	SLS Block 1	E-DSM-V-E-DSM-E-J	7.1 - 12.2	11	8840	3.9
Tour III (**flyby** of 2013 AU160, **rendezvous** w/ Narcissus)	11/2029	Atlas V 551	V-E-E-J	9.2 - 13	10	4710	2.8

Committee, 2015) *LSST* (Ivezic et al., 2008), and the planned and proposed space telescopes *JWST* (Milam et al., 2016) and *WFIRST* (Holler et al., 2017), will greatly improve our characterization of the Centaur population, and may provide the foundation for a potential multi-body Centaur tour mission in the decades to come.

Because of the difficulty in selecting a tour or rendezvous trajectory, the best opportunity to address the science goals identified required a flyby of a single, high-value Centaur system. Of potential targets, 2060 Chiron and 10199 Chariklo were the complex Centaur systems identified that could be reached in the time frame specified by the NFAO4. Chiron exhibits confirmed cometary behavior and a possible ring system (Ortiz et al., 2015; Luu and Jewitt, 1990). However, the ring system of Chiron is unconfirmed (Ortiz et al., 2015) and the Centaur would be too far from the Sun during observation to exhibit a coma. While cometary activity has not been observed for Chariklo, it exhibits a confirmed double ring system (Braga-Ribas et al., 2014). Thus, we identify a single flyby encounter of Chariklo as the best opportunity to retrieve high-value science for this Centaur reconnaissance concept.

Table 3: Science Objectives (SOs), which support the high-level Science Goals (SGs). Each objective can be traced to a Priority Question from Vision and Voyages for Planetary Sciences in the Decade 2013-2022 (National Research Council, 2011, pp. 3–3) (see table 1).

Sci. Goal	Science Objective	
SG1	1.1	Determine if the surface of Chariklo, a Centaur, is more like that of Phoebe, Ceres, Pluto, Charon, or comets at present by investigating the near-surface presence and abundance of ices (including H_2O, CH_3OH, CO_2, CO, CH_4, N_2, NH_3, HCN) and minerals (Fe^{2+}, OH, and H_2O-bearing), mapping variations in the surface temperature, and identifying geologic features (impact craters, flow features, mass wasting, and tectonic features).
	1.2	Determine if differences in color on Centaurs are a result of the cumulative effect of impacts, coma activity, or other processes, by correlating color to the relative age of the surface.
SG2	2.1	Determine whether the rings around Chariklo are a product of (1) the coma (volatile composition of the surface), (2) material ejected through impacts (bulk composition of the upper crust), or (3) captured external material (does not match previous two).
	2.2	Measure physical properties of the rings and whether the impactor-induced ejecta plume interacts with or changes physical properties of the ring system.
SG3	3.1	Determine if Centaurs originate from solar, terrestrial, cometary, or other solar system reservoirs by measuring composition, speciation, and isotopic ratios (D/H, O, N, and C) of the Centaur near-surface materials and comparing these measurements to those made at other bodies and with models of solar system formation.

2.4. *Science Objectives for 10199 Chariklo Encounter*

10199 Chariklo has an orbital period of 63 years with an eccentricity of 0.17, and will be progressing out of the ecliptic (inclination of 23 deg.) towards aphelion along at the time of the conceptual encounter (JPL SSD, 2017). The body is slightly redder than the sun, though very dark, with a geometric albedo of only 0.045. For an 18 AU encounter, no outgassing activity is expected. Having identified Chariklo as the best accessible science target, we developed a focused, Chariklo specific list of Science Objectives (SOs). Each of the six defined SOs is directly traceable to a specific Science Goal (Table 3).

The first two Science Objectives support SG1. The first objective (SO1.1) is to produce a geological and compositional map of the surface to identify the dominant processes that modify the surface. The second objective (SO1.2) is to relate surface geology, chemistry, and color with each other to test whether surface modification is related to the bimodal color distribution observed for Centaurs and KBOs.

The next two Science Objectives support SG2. By comparing the bulk composition and abundances of volatile species on Chariklo's surface and subsurface with the ring system (SO2.1), the mission concept would identify the ring formation mechanisms. A ring enriched in surface particles ejected by volatile outgassing may indicate a coma origin. A ring system with a

Power	3 MMRTGs (209 W End of Life Power)
ACS	4 reaction wheels using sun and star trackers
Mechanical	Scanning platform for instruments
Telecom	3 meter high-gain X-band antenna
C&DH	1 flight computer w/768 Gb data capacity
Propulsion	4 x 22 N and 24 x 0.9 N hydrazine engines
Thermal	Active fluid heating and passive radiators
Ground	34 m dish on DSN X-band only

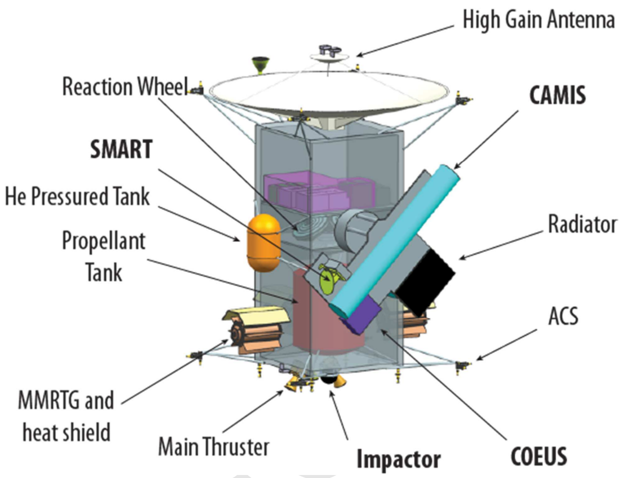

Figure 2. Summary table and schematic showing the location of the baseline instruments, impactor, and other spacecraft components for the mission concept.

different bulk composition than Chariklo may indicate that the ring material is sourced from a different body (i.e., impact or capture). A ring system with the same bulk composition and/or volatile abundances as the surface and subsurface would indicate that the material was ejected from Chariklo in an impact or as debris due to outgassing. This ambiguity would be reduced by comparing the properties of an impactor-induced ejecta plume to those of the ring system (SO2.2).

The final Science Objective supports SG3. The mission concept would characterize the chemistry of Chariklo's surface and subsurface (SO3.1) and use this to constrain the original reservoir for the volatiles present. A comparison of these measurements to other solar system bodies (JFCs, P- and D-type asteroids, Trojan asteroids, etc.) may also identify common chemical processes that have occurred on small, primitive bodies since solar system formation.

3. Science Instrumentation

We present a Chariklo flyby-with-impactor mission concept that would carry a moderate science payload, modeled on previously flown instruments, that is capable of addressing the outlined science objectives (Figure 2, Table 4). The remote-sensing instruments are co-aligned on an articulated scanning platform, allowing the spacecraft to fully scan the Centaur surface during the encounter, with simultaneous radio science and instrument measurements.

3.1. Halberd (Impactor)

Named for the weapon used by Botticelli's Camilla to tame a Centaur, Halberd is a 100 kg tungsten impactor. Tungsten was chosen because it is relatively dense and inert. Released five days before launch, Halberd would collide with Chariklo at approximately the flyby velocity, ejecting approximately 10^6 kg of surface and subsurface material to a maximum of ~10 m depth for compositional analysis. Comparing the properties of ejected material to the surface would help to constrain the role of space weathering in altering the spectral (color) properties of Centaur surfaces, and understand the mechanism(s) behind ring formation and evolution, and plume spectra might help constrain the origin of Chariklo's ice within the solar system. The impactor design draws conceptually on the Deep Impact mission (Hampton et al., 2005), which successfully deployed a projectile to study the structure and subsurface composition of comet Tempel 1 (A'Hearn et al., 2005).

We did not explore an instrumented or guided "smart" impactor within the scope of this study. We anticipate that the additional heat, power, and data requirements of a smart impactor may significantly affect the overall system requirements and cost. However, the introduction of some impactor trajectory control may reduce the risk of the impactor missing Chariklo, and the addition of a small impactor science payload may significantly enhance the scientific return.

3.2. *CAMIS* (Camera and VIS/IR Spectrometer)

The Centaur Advanced Multi-wavelength Imager and Spectrometer (CAMIS) is a shared-optic, combination visible imager and infrared spectrometer based on the High Resolution Imager (HRI) from the Deep Impact mission (Hampton et al., 2005). CAMIS would enable the geologic and spectral mapping needed to illuminate the relationship between surface features, composition, and color/spectra. It would further produce high-resolution maps of the rings and their particles, as well as the ejecta plume, which may constrain the volatile composition, and understand the relationship between outgassing and the ring formation and evolution. As conceptualized within this study, CAMIS features a 30 cm aperture telescope with a 230 cm focal length, and the visible imager has a filter wheel with five 100 nm bandpass channels covering 300-900 nm, and 1 broadband panchromatic filter covering the entire 300-900 nm range. The infrared spectrometer has a spectral range of 0.9-5 μm with a spectral resolution of 4 nm.

Table 4: Instrument overview. See Section 3 for further information.

Name	Instrument	Mass [kg]	Power [W]	Scientific Contribution
Halberd	Impactor	100	0	**(SG1-3)** Excavate near- and sub-surface material in an ejecta plume that can be characterized to better understand the geologic evolution of Chariklo, the origin of the ring system, and the origin of the body at formation
CAMIS	Camera + VIS/IR Spec.	52	29	**(SG1-2)** Enable geologic mapping to contextualize all other observations **(SG2)** Provide spatial distribution and presence of ice/rock species
SMART	Sum-mm Spec.	10	40	**(SG1)** Thermally map the surface to constrain current and past surface processes **(SG2)** Relate ejecta chemistry to rings to constrain ring formation **(SG3)** Determine isotope ratios (H_2O, NH_3, and CO) to constrain the Centaur's origins and grouping among the solar system bodies
COEUS	UV Spec.	4.4	4	**(SG1)** Spectrally map the surface for comparison with geologic map **(SG2)** Permit comparative analysis of ring and ejecta plume physical and chemical properties **(SG3)** Partially constrain origin via noble gas (Ne, Ar) detection
CERSE	Radio	< 1	< 1	**(SG1-2)** Constrain mass distribution of the Chariklo system

3.3. *SMART* (Sub-Millimeter Spectrometer)

The Sub-Millimeter Articulated Reconnaissance Telescope (SMART) is an estimated 10 kg instrument that consists of a sub-mm spectrometer and radiometer based on Rosetta's MIRO (Gulkis et al., 2007), assuming advances in instrument mass and performance. SMART would provide isotopic ratios (D/H as well as H_2O, NH_3, and CO) of Chariklo's rings and the impact plume produced by Halberd, as was demonstrated successfully by MIRO at comet 67P (e.g. Gulkis et al 2015, Lee et al. 2015). This information would help determine Chariklo's origin in the solar system, and constrain the ring formation mechanism. Additionally, SMART would provide high-resolution thermal maps of Chariklo's surface that will help determine the geologic evolution of the body to its present-day state, in particular the impact history, resurfacing, and crater burial resulting from dust infall.

3.4. *COEUS* (UV Spectrometer)

The Centaur Occultation Ejecta Ultraviolet Spectrometer (COEUS) is a UV imaging spectrometer based on New Horizons' P-Alice (Stern et al., 2008). Further iteration of this mission concept might consider Europa Clipper's Ultraviolet Spectrograph (Europa-UVS) (Retherford et al., 2015), a modern version of ALICE, given that the detectors produced for ALICE are no longer manufactured. The conceptual COEUS instrument includes a 20-pixel imaging array and 450 spectral channels sensitive from 50-185 nm with a spectral resolution of <1.2 nm (extended source). COEUS would perform reflectance spectroscopic analysis of the sunlit surface during the approach to Chariklo to detect the presence of volatiles on the surface and to determine if any coma activity is present. A similar measurement was conducted with the Cassini UV spectrometer upon a flyby past Phoebe, suspected to be a captured Centaur (Brown, 2000), at a similar velocity and surface albedo (Hendrix and Hansen, 2008) just prior to Saturn orbit insertion. That study was able to detect water ice and constrain models of water ice and non-water ice components. Spectroscopic analysis of the rings and ejecta plume using the sun as a UV source (in reflectance on approach and in transmission and reflectance on departure) at multiple phase angles would provide information on ring and plume particle size and composition. A similar analysis was conducted by Voyager 2 at Neptune (Broadfoot et al., 1989) using a stellar UV source, which may also be possible within this mission concept pending further analysis.

3.5. CERSE (Radio Science)

Finally, we conceptualize a Centaur Radio Science Experiment (CERSE), whereby the Chariklo system occults the radio transmission between the Earth and the spacecraft to help determine the distribution of matter within the ringed system, and identify additional rings. Augmenting the telecommunication system with an ultra-stable oscillator provides a frequency reference for one-way downlink, enabling these occultation experiments. This addition comes at a minimal cost for mass (< 1 kg) and power (< 1 W). Radio signal tracking of the spacecraft would also be used to produce Doppler measurements that may constrain the mass and J2 of Chariklo, given shape models produced by CAMIS on approach.

3.6. Encounter Science Timeline and Deliverables

The conceptual encounter timeline and data return is summarized in Figure 3. At a flyby velocity of 9.3 km/s, Chariklo first becomes resolvable beyond a single pixel approximately 8 months prior to closest approach. Course correction, exposure planning, shepherd moon and hazard detection, and shape modeling activities begin after this milestone. The ~ 20 km wide ring system is resolvable approximately four weeks prior to closest approach. Due to the high albedo of the inner ring, the imaging instruments are sufficiently sensitive to detect the ring system at these distances.

The primary science encounter would return high-resolution (100 - 200 m/px) images in full color and over the full spectral range of CAMIS, thermal global mosaics, and ~ 50 m/px resolution ring-to-ring, pole-to-pole full color and thermal mosaics for a single ~ 100 km swath. Sub-mm spectra would be taken alongside thermal maps, and UV point spectra would be continuously recorded in the direction of the camera throughout the imaging sequence. By comparing the radio signal strength between Earth and the spacecraft as the limb and ring material cross the line of sight of the spacecraft from the Earth, we would measure the number of rings as well as their density and distribution. UV spectra would be obtained when Chariklo occults the Sun by the spacecraft's UV spectrometer.

4. New Frontiers class mission concept

To integrate the science and engineering requirements into a consistent spacecraft design concept, we utilized JPL's concurrent design facilities in cooperation with TeamX. The resulting conceptual spacecraft houses a state-of-the-art science payload capable of achieving the proposed objectives, and subsystems that comply with the cost, mass, power, and trajectory constraints of a New Frontiers mission as defined by the NFAO4 (National Aeronautics and Space Administration, 2016).

Cost requirements are prescribed by the New Frontiers mission call, and include a Principal Investigator (PI) managed cost cap of $850M (FY15), not including launch costs, for Phase A through D. Launch constraints derive from the launch service available for a New Frontiers investigation. The NFAO4 provides a single expendable launch vehicle (ELV) to deliver payload to the target body at no charge to the PI-managed cost (NRC, 2011). The presented mission concept utilizes the Atlas V 401 launch vehicle to maximize our spacecraft mass allowance and

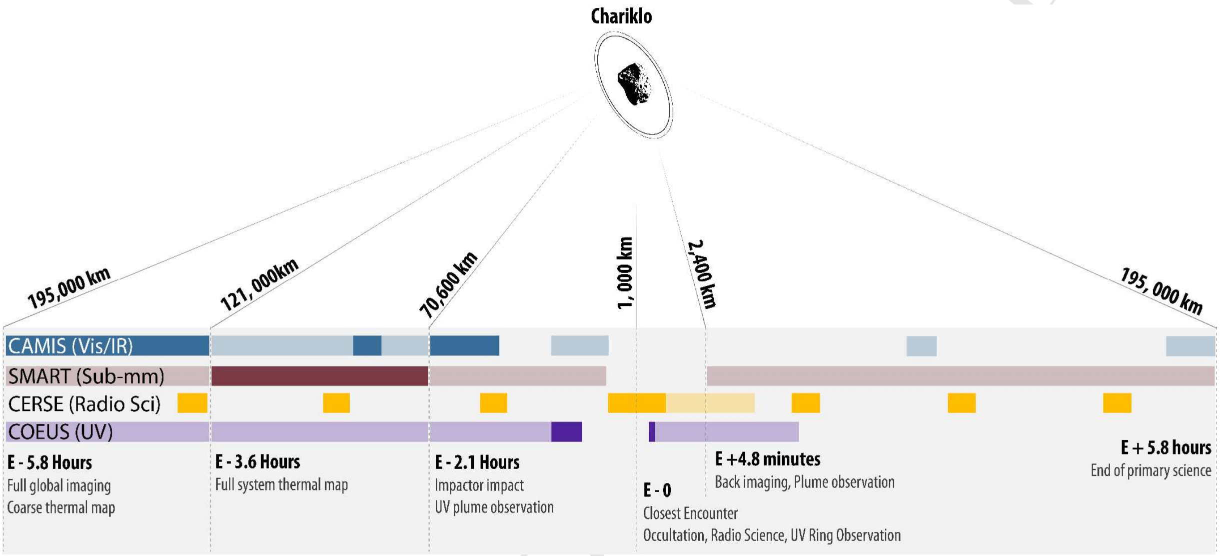

Figure 3. Summary of encounter science showing when instruments are active (colored bars) and when instruments are making critical observations (bold colors) for the mission review science goals and objectives.

enable operations into the outer solar system, including a Jupiter flyby. Furthermore, the payload choice, spacecraft architecture, and propulsion design constrain power requirements during the cruise phase, trajectory maneuvers, and the critical science measurements during the encounter phase. Further, mission design options were restricted to launch opportunities between the years 2020-2030 as permitted by the NFAO4.

The presented 13.4 year conceptual mission would launch in September, 2026, followed by one Venus gravity assist, two Earth gravity assists, and one Jupiter gravity assist. The flyby of Chariklo would occur at 18 AU and 9.3 km/s, with a closest approach of 1,000 km in January 2040. Six months prior to closest approach, periodic measurements would be taken to detect and characterize any present shepherd moons or outgassing, as well as to characterize the photometry, rotation, and shape of the body. The spacecraft would release a non-instrumented tungsten impactor five days before closest approach to excavate surface material for observation. Continuous observations of Chariklo would commence six hours before closest approach and continue for six hours after closest approach. Over the following year, scientific data from the encounter would be relayed to Earth. The long period spent en route to the target (quiet cruise stage) of the presented mission concept, the distance of the encounter to Earth, post-encounter data transmission, and the pointing requirements of the impactor all influence the spacecraft design and trade space. As configured, there is a 30% growth allowance in mass and power margins.

4.1. *Mission Design*

Chariklo is in an eccentric orbit (*e* = ~0.17) between Saturn and Uranus, inclined with respect to the ecliptic by ~ 23 degrees, with a semi-major axis of approximately 15.8 AU. The orbit of Chariklo necessitates that the spacecraft undergo a Jupiter gravity assist. Programmatic constraints on mission duration (< 15 yr), launch timeframe (launch between 2020 and 2030),

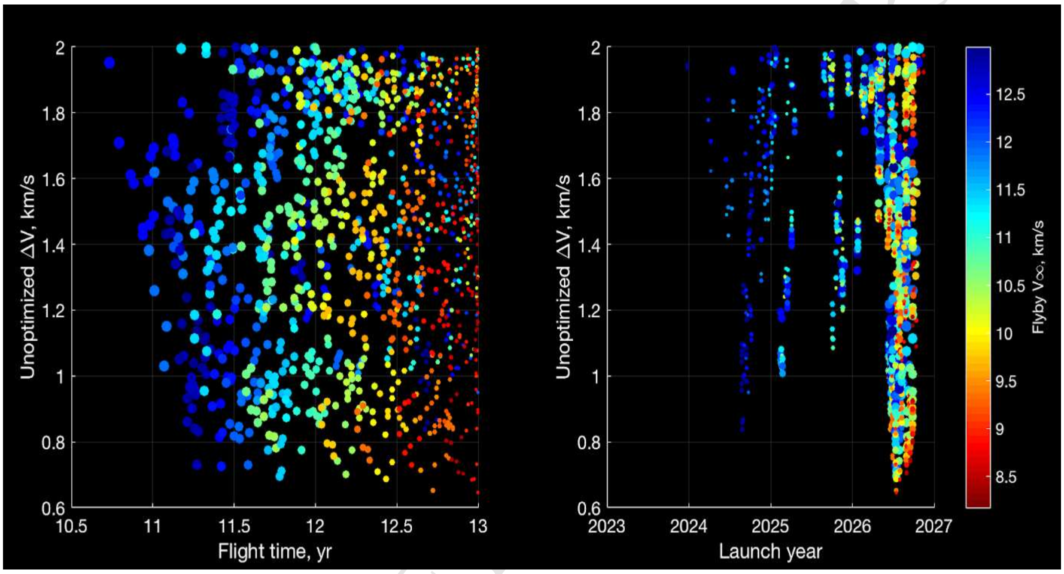

Figure 4. Launch opportunities (colored circles) for a Chariklo flyby mission. The left panel shows un-optimized ΔV vs. flight time to Chariklo. The right panel shows un-optimized ΔV vs. launch date. Un-optimized ΔV includes launch, but excludes trajectory correction maneuvers and a possible kinetic impactor separation maneuver. Circles are colored according to flyby speeds.

and propellant mass excluded all trajectories that would allow an extended rendezvous of the spacecraft with Chariklo.

Conceptual mission design options satisfying the above constraints are summarized in Figure 4. No launch opportunities were found before 2024 due to an unfavorable conjunction with Jupiter, and no low ΔV transfers were found later than July 2027. Most trajectories involve a sequence of gravity assists that visit Venus once, Earth twice, and Jupiter once, and some require additional low ΔV deep space maneuvers. The ΔV values provided are approximate in the sense that they do not account for trajectory correction maneuvers during the final approach to Chariklo, or for a possible kinetic impactor separation maneuver. Time of flight estimates for the several identified opportunities from launch to a Chariklo encounter range from 11 to 13 years. Chariklo encounter speeds vary from 8–13 km/s.

The mission design selected for the proposed concept is shown in Figure 5. The trajectory is structured around a ballistic flyby opportunity of Jupiter in October 2031 that allows for a low

ΔV transfer to Chariklo's inclined orbit. Following a 2026 launch, the conceptual trajectory includes three gravity assists (Venus, Earth, Earth) between February 2027 and December 2029, as well as a deep space maneuver in July 2027. The resulting intercept trajectory leads to an encounter with Chariklo in June 2039. At that time, the spacecraft would be 18 times further from the Sun as the Earth travelling at a speed of 9.3 km/s relative to Chariklo. The low launch requirements allow for a spacecraft wet mass of roughly 1750 kg launched with an Atlas V 401 (Table 2).

4.2. Spacecraft Configuration and Design

To obtain full-body coverage of Chariklo during a single flyby, this mission concept incorporates co-pointed science instruments mounted on a scan platform, allowing them to articulate with respect to the spacecraft and sweep the Centaur surface (Figure 2). While developing the conceptual science experiment and spacecraft subsystem, we considered three

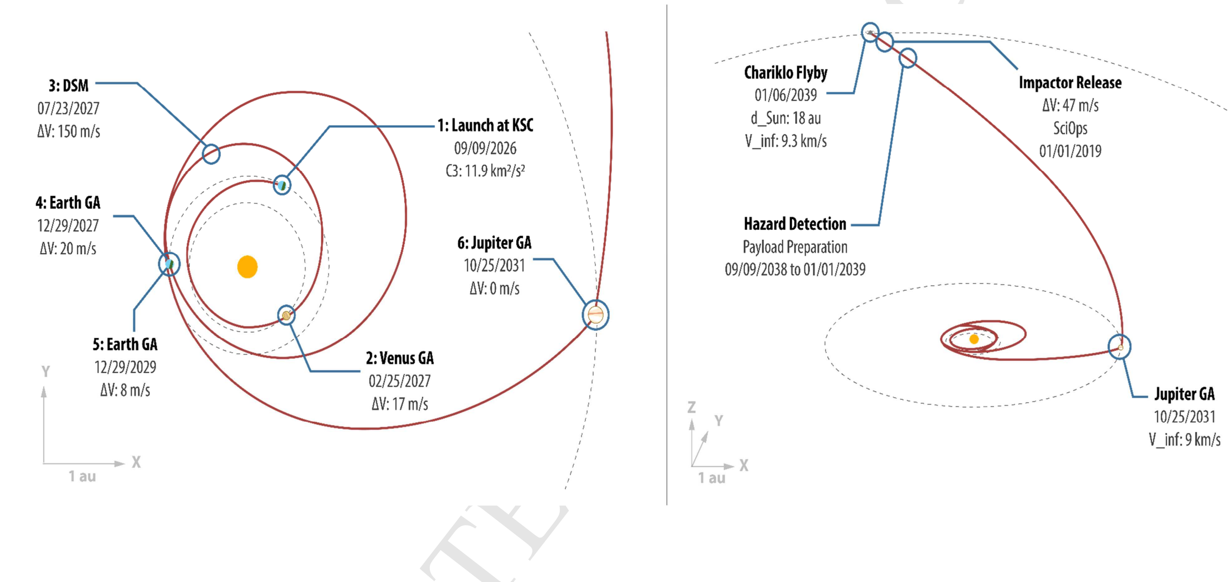

Figure 5. Summary of 09/09/2026 launch opportunity. Chariklo flyby trajectory, including dates and ΔV values for each maneuver are shown. One deep space maneuver (DSM) and gravity assists (GM) with Venus and Earth allow for a low characteristic energy (C3) at the proposed launch date. A ballistic flyby of Jupiter in 2031 propels the spacecraft out of the ecliptic onto an intercept trajectory with Chariklo.

key trades.

(1) We considered the implementation of solar arrays so that the conceptual mission was not restricted by access to radioisotope thermoelectric generators (RTGs), which are costly in comparison and are a limited resource. However, the power needs of the proposed system during its cruise stage would require solar panels with a total area of 250 m^2, corresponding to a system mass increase of 1148 kg. The additional mass associated with the use of solar panels would exceed the capability of the launch vehicle.

(2) We considered whether an articulated antenna could substitute for a scan platform to reduce complexity. An articulated antenna would allow the spacecraft to point inarticulate instruments by positioning the spacecraft itself, maintaining the capability to perform simultaneous radio and instrument science. Based on our limited analysis, this option might only have a marginal effect on spacecraft pointing precision while reducing cost and risk. Therefore,

such a configuration would be considered in future iterations.

(3) We considered how best to place the payload platform. The spacecraft was configured so that the radio dish would allow contemporaneous instrument and radio science without impeding the instrument field of view. This configuration has a reduced margin for fitting within the launch vehicle fairing, but improves the science return of the flyby event.

The mass and power requirements for each subsystem are presented in Figure 6. A description of each subsystem follows:

Propulsion: The spacecraft concept utilizes a regulated, dual-branch monopropellant chemical system. The conceptual propulsion system, including all the tanks, lines, valves, thrusters, and regulators, would use currently available parts. Four main thrusters are used for trajectory correction maneuvers. To provide thruster attitude control, a cluster of three RCS thrusters arranged orthogonally are placed at the spacecraft's eight "corners" (Figure 2).

Power: The conceptual power system consists of a rechargeable secondary battery and three multi-mission radioisotope thermoelectric generators (MMRTGs) to provide ~ 210 W at 18 AU. Using only the radioisotope power system, the spacecraft is power positive in safe mode, quiet cruise, and recharge modes. An 8 kWh equivalent secondary battery supplements power in other modes. Some power negative modes have recharge times that affect the mission requirements. After the encounter, the spacecraft would alternate between the critical event cruise mode for 8 hours (data transmission) and recharge mode for 9.3 hours. The power system is single fault tolerant, with a 43% margin in power generation.

Thermal Systems: The conceptual temperature regulation system is divided into three separate zones that utilize a combination of active and passive heating: (1) the electronics box and propellant tank, (2) the propulsion fuel lines, and (3) the payload electronics. As an additional thermal consideration, the radio dish would be coated with a thermally reflective paint that enables its use as a solar shield for the radiators during inner solar system maneuvers.

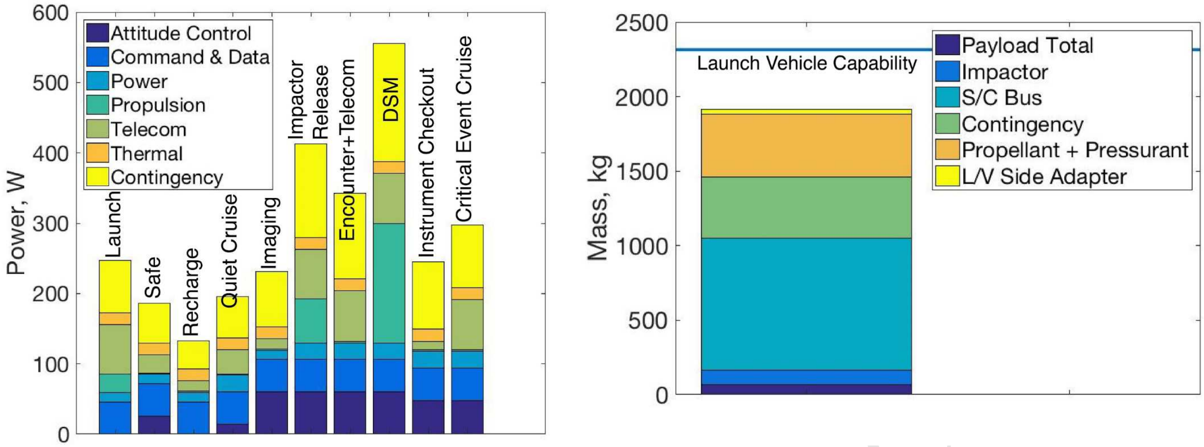

Figure 6. Summary of (left) power usage by each subsystem for every power mode, and (right) mass by subsystem. DSM denotes a deep space maneuver.

Attitude Control System: The most stringent spacecraft concept pointing requirements are driven by the pointing precision required to release the impactor on an intercept trajectory with Chariklo. A combination of reaction wheels and thrusters exceeds these pointing requirements, which provides a 3σ certainty to impact within 30 km of a targeted point. The ACS capabilities would also allow for a 180-degree slew over 90 seconds at closest approach, providing a redundant targeting capability for the instruments during the science encounter. If the reaction wheels malfunctioned and tripped the spacecraft into safe mode, the RCS thrusters are capable of maintaining the spacecraft orientation.

Command and Data Handling: 768 Gb of onboard storage easily accommodates the predicted 20.4 Gb (uncompressed) science encounter data and the 45 Gb (uncompressed) total volume of science data collected during the 12 hour encounter. The amount of data collected is limited by the size of the object, the pointing precision and scan rate of the instruments, and the velocity of the flyby relative to the body. The radiation hardened CPU selected for this concept has been previously flown on the Mars Reconnaissance Orbiter, Curiosity Mars Rover, and Juno spacecraft. We did not explore software requirements or design for spacecraft subsystems.

Telecommunications: The conceptual spacecraft includes a 3 m diameter fixed high-gain X-band primary antenna. Two low gain horns facilitate communication while the spacecraft is within the orbit of Mars. All data could be recovered in ~ 12 months following the science encounter, assuming 8 hours per day and onboard processing that allows for 4:1 data compression before transmission. All telecom system components are flight proven, and the system as a whole shares significant architecture with the Cassini mission.

4.3. Identified Risk

The key risk identified by the study review panel is associated with integration timelines for the co-pointed instrument platform and impactor, which could cause delays in delivering the spacecraft for launch. Further, a failure of the scan platform would prevent radio occultation measurements after closest approach, because the spacecraft would then be used to point the instruments at the target during solar occultation. To mitigate these risks, further iteration should consider fixed instruments and an articulated antenna, which would reduce the complexity and number of moving parts associated with the instrument package and would likely result in only a small loss of pointing precision.

Additionally, the nature of the Chariklo system is uncertain, and unobserved rings, dust, cometary ejecta, shepherd moons, and other system hazards may be present. The conservative flyby altitude at closest approach chosen for this mission concept (1,000 km) mitigates dust and debris impact hazards.

Another large risk is the potential failure of the impactor either to deploy or to hit the target. Such a failure would prevent D/H measurements, a key isotopic ratio in understanding Chariklo's origin, and would reduce the ability of the conceptual mission to constrain the formation and dynamics of the ring system. Considering a self-propelled and perhaps instrumented "smart impactor" may improve the reliability of the impactor to deploy and hit the target. However, such a trade may come at increased mass, cost, and data requirements that must be fully explored.

5. Preliminary Discovery Class Analysis

We briefly explored whether a modified version of the presented mission concept is feasible under a Discovery cost-cap ($450M FY2015), reducing the instrument payload to the visible camera, the VIS-IR mapping spectrometer, and impactor. Without a UV instrument, some characterization of the physical and chemical properties of the rings and ejecta plume are lost. However, the science return from this payload would address a preponderance of the SOs relating to the origin of variation in Centaur color and of Chariklo's ring system.

The Phase A–D Discovery cost was estimated to be 16% over the Discovery program cost cap for the current call, but is only a few percent beyond the $495M FY2019 cost cap of the next discovery call. Additionally, this cost was estimated using a New Frontiers schedule, and further development could reduce the mission cost to be within the cap of the future discovery calls. For the presented design, a future Discovery call would have to furnish three MMRTGs or two potential enhanced MMRTGS (eMMRTGs), as well as launch compliance with the National Environmental Policy Act (NEPA), at no cost.

6. Conclusion

We presented a cost-effective flyby of 10199 Chariklo, a Centaur object with a double ring system. Because Centaurs share properties with other classes of small bodies, including Kuiper Belt Objects, comets, and asteroids, and because Chariklo exhibits a ring system, this mission concept stands to address many crosscutting questions at the forefront of NASA's goals in planetary science. While the primary effort was exploring a low-cost New Frontiers class concept, further analysis of potential power solutions may produce a viable Discovery class mission concept.

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References

A'Hearn, M.F., Belton, M.J.S., Delamere, W.A., Kissel, J., Klaasen, K.P., McFadden, L.A., Meech, K.J., Melosh, H.J., Schultz, P.H., Sunshine, J.M., Thomas, P.C., Veverka, J., Yeomans, D.K., Baca, M.W., et al., 2005, Deep Impact: Excavating Comet Tempel 1: Science, v. 310, p. 258–264, doi: 10.1126/science.1118923.

Bauer, J.M., Fernández, Y.R., and Meech, K.J., 2003, An optical survey of the active Centaur C/NEAT (2001 T4): Publications of the Astronomical Society of the Pacific, v. 115, p. 981.

Bauer, J.M., Grav, T., Blauvelt, E., Mainzer, A.K., Masiero, J.R., Stevenson, R., Kramer, E., Fernández, Y.R., Lisse, C.M., and Cutri, R.M., 2013, Centaurs and scattered disk objects in the thermal infrared: Analysis of WISE/NEOWISE observations: The Astrophysical Journal, v. 773, p. 22.

Braga-Ribas, F., Sicardy, B., Ortiz, J.L., Snodgrass, C., Roques, F., Vieira-Martins, R., Camargo, J.I.B., Assafin, M., Duffard, R., and Jehin, E., 2014, A ring system detected around the Centaur (10199) Chariklo: Nature, v. 508, p. 72–75.

Broadfoot, A.L., Atreya, S.K., Bertaux, J.L., Blamont, J.E., Dessler, A.J., Donahue, T.M., Forrester, W.T., Hall, D.T., Herbert, F., Holberg, J.B., Hunter, D.M., Krasnopolsky, V.A., Linick, S., Lunine, J.I., et al., 1989, Ultraviolet Spectrometer Observations of Neptune and Triton: Science, v. 246, p. 1459–1466, doi: 10.1126/science.246.4936.1459.

Brown, M.E., 2000, Near-Infrared Spectroscopy of Centaurs and Irregular Satellites: The Astronomical Journal, v. 119, p. 977, doi: 10.1086/301202.

Campins, H., Telesco, C.M., Osip, D.J., Rieke, G.H., Rieke, M.J., and Schulz, B., 1994, The color temperature of (2060) Chiron: A warm and small nucleus: The Astronomical Journal, v. 108, p. 2318–2322.

Combi, M.R., Harris, W.M., and Smyth, W.H., 2004, Gas dynamics and kinetics in the cometary coma: Theory and observations: Comets II, v. 1, p. 523–552.

Cruikshank, D.P., Roush, T.L., Bartholomew, M.J., Geballe, T.R., Pendleton, Y.J., White, S.M., Bell, J.F., Davies, J.K., Owen, T.C., de Bergh, C., Tholen, D.J., Bernstein, M.P., Brown, R.H., Tryka, K.A., et al., 1998, The Composition of Centaur 5145 Pholus: Icarus, v. 135, p. 389–407, doi: 10.1006/icar.1998.5997.

Di Sisto, R.P., and Brunini, A., 2007, The origin and distribution of the Centaur population: Icarus, v. 190, p. 224–235, doi: 10.1016/j.icarus.2007.02.012.

Emery, J.P., Marzari, F., Morbidelli, A., French, L.M., and Grav, T., 2015, The Complex History of Trojan Asteroids: arXiv:1506.01658 [astro-ph], doi: 10.2458/azu_uapress_9780816532131-ch011.

Epifani, E.M., Palumbo, P., Capria, M.T., Cremonese, G., Fulle, M., and Colangeli, L., 2006, The dust coma of the active Centaur P/2004 A1 (LONEOS): a CO-driven environment? Astronomy & Astrophysics, v. 460, p. 935–944, doi: 10.1051/0004-6361:20065189.

Gladman, B., Kavelaars, J.J., Petit, J.M., Morbidelli, A., Holman, M.J. and Loredo, T., 2001, The structure of the Kuiper belt: Size distribution and radial extent: The Astronomical Journal, v. 122, p.1051.

Grundy, W.M., Stansberry, J.A., Noll, K.S., Stephens, D.C., Trilling, D.E., Kern, S.D., Spencer, J.R., Cruikshank, D.P., and Levison, H.F., 2007, The orbit, mass, size, albedo, and density of (65489) Ceto/Phorcys: A tidally-evolved binary Centaur: Icarus, v. 191, p. 286–297, doi: 10.1016/j.icarus.2007.04.004.

Gulkis, S., Frerking, M., Crovisier, J., Beaudin, G., Hartogh, P., Encrenaz, P., Koch, T., Kahn, C., Salinas, Y., Nowicki, R., Irigoyen, R., Janssen, M., Stek, P., Hofstadter, M., et al., 2007, MIRO: Microwave Instrument for Rosetta Orbiter: Space Science Reviews, v. 128, p. 561–597, doi: 10.1007/s11214-006-9032-y.

Gulkis, S. et al., 2015, Subsurface properties and early activity of comet 67P/Churyumov-Gerasimenko: Science, 347(6), p.aaa0709.

Hampton, D.L., Baer, J.W., Huisjen, M.A., Varner, C.C., Delamere, A., Wellnitz, D.D., A'Hearn, M.F., and Klaasen, K.P., 2005, An Overview of the Instrument Suite for the Deep Impact Mission: Space Science Reviews, v. 117, p. 43–93, doi: 10.1007/s11214-005-3390-8.

Hendrix, A.R., and Hansen, C.J., 2008, Ultraviolet observations of Phoebe from the Cassini UVIS: Icarus, v. 193, p. 323–333, doi: 10.1016/j.icarus.2007.06.030.

Holler, B.J., Milam, S.N., Bauer, J.M., Alcock, C., Bannister, M.T., Bjoraker, G.L., Bodewits, D., Bosh, A.S., Buie, M.W., Farnham, T.L., Haghighipour, N., Hardersen, P.S., Harris, A.W., Hirata, C.M., et al., 2017, Solar system science with the Wide-Field InfraRed Survey Telescope (WFIRST): arXiv:1709.02763 [astro-ph], http://arxiv.org/abs/1709.02763 (accessed January 2018).

Horner, J., Evans, N.W., and Bailey, M.E., 2004, Simulations of the population of Centaurs – I. The bulk statistics: Monthly Notices of the Royal Astronomical Society, v. 354, p. 798–810, doi: 10.1111/j.1365-2966.2004.08240.x.

Hyodo, R., Charnoz, S., Genda, H., and Ohtsuki, K., 2016, Formation of Centaurs' Rings through Their Partial Tidal Disruption during Planetary Encounters: The Astrophysical Journal Letters, v. 828, p. L8, doi: 10.3847/2041-8205/828/1/L8.

Ivezic, Z., Tyson, J.A., Abel, B., Acosta, E., Allsman, R., AlSayyad, Y., Anderson, S.F., Andrew, J., Angel, R., Angeli, G., Ansari, R., Antilogus, P., Arndt, K.T., Astier, P., et al., 2008, LSST: from Science Drivers to Reference Design and Anticipated Data Products: arXiv:0805.2366 [astro-ph], http://arxiv.org/abs/0805.2366 (accessed April 2018).

Jewitt, D., 1999, Kuiper belt objects: Annual Review of Earth and Planetary Sciences, v. 27, pp. 287-312.

JPL Solar System Dynamics, 2017, JPL Small-Body Database Search Engine:, https://ssd.jpl.nasa.gov/sbdb_query.cgi.

Lee, S. et al., 2015, Spatial and diurnal variation of water outgassing on comet 67P/Churyumov-Gerasimenko observed from Rosetta/MIRO in August 2014: Astronomy and Astrophysics, 583, p.A5.

Luu, J., and Jewitt, D., 1996, Color diversity among the Centaurs and Kuiper belt objects: The Astronomical Journal, v. 112, p. 2310.

Luu, J.X., and Jewitt, D.C., 1990, Cometary activity in 2060 Chiron: The Astronomical Journal, v. 100, p. 913–932, doi: 10.1086/115571.

Luu, J.X., and Jewitt, D.C., 2002, Kuiper belt objects: Relics from the accretion disk of the sun: Annual Review of Astronomy and Astrophysics, v. 40, pp. 63-101.

Melita, M.D., Duffard, R., Ortiz, J.L., and Campo-Bagatin, A., 2017, Assessment of different formation scenarios for the ring system of (10199) Chariklo: Astronomy & Astrophysics, v. 602, p. A27, doi: 10.1051/0004-6361/201629858.

Meech, K.J., and Svoren, J., 2004, Comets II ed MC Festou: HU Keller and HA Weaver (Tucson, AZ/Houston, TX: Univ. of Arizona Press/Lunar Planet. Inst.), v. 317.

Milam, S.N., Stansberry, J.A., Sonneborn, G., and Thomas, C., 2016, The James Webb Space Telescope's Plan for Operations and Instrument Capabilities for Observations in the Solar

System: Publications of the Astronomical Society of the Pacific, v. 128, p. 018001, doi: 10.1088/1538-3873/128/959/018001.
National Aeronautics and Space Administration, 2016, Announcement of Opportunity, New Frontiers 4: Washington, DC, NNH16ZDA011O.
National Research Council, 2011, Vision and Voyages for Planetary Science in the Decade 2013-2022: Washington, DC, The National Academies Press, doi: 10.17226/13117.
Noll, K.S., Levison, H.F., Grundy, W.M., and Stephens, D.C., 2006, Discovery of a binary Centaur: Icarus, v. 184, p. 611–618, doi: 10.1016/j.icarus.2006.05.010.
Ortiz, J.L., Duffard, R., Pinilla-Alonso, N., Alvarez-Candal, A., Santos-Sanz, P., Morales, N., Fernández-Valenzuela, E., Licandro, J., Bagatin, A.C., and Thirouin, A., 2015, Possible ring material around centaur (2060) Chiron: Astronomy & Astrophysics, v. 576, p. A18, doi: 10.1051/0004-6361/201424461.
Ortiz, J.L., Santos-Sanz, P., Sicardy, B., Benedetti-Rossi, G., Bérard, D., Morales, N., Duffard, R., Braga-Ribas, F., Hopp, U., Ries, C., Nascimbeni, V., Marzari, F., Granata, V., Pál, A., et al., 2017, The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation: Nature, v. 550, p. 219, doi: 10.1038/nature24051.
Pan, M., and Wu, Y., 2016, On the Mass and Origin of Chariklo's Rings: The Astrophysical Journal, v. 821, p. 18, doi: 10.3847/0004-637X/821/1/18.
Peixinho, N., Delsanti, A., Guilbert-Lepoutre, A., Gafeira, R., and Lacerda, P., 2012, The bimodal colors of Centaurs and small Kuiper belt objects: Astronomy & Astrophysics, v. 546, p. A86, doi: 10.1051/0004-6361/201219057.
Pike, R.E., Fraser, W.C., Schwamb, M.E., Kavelaars, J.J., Marsset, M., Bannister, M.T., Lehner, M.J., Wang, S.-Y., Alexandersen, M., Chen, Y.-T., Gladman, B.J., Stephen Gwyn, Petit, J.-M., and Volk, K., 2017, Col-OSSOS: z -Band Photometry Reveals Three Distinct TNO Surface Types: The Astronomical Journal, v. 154, p. 101, doi: 10.3847/1538-3881/aa83b1.
Retherford, K.D., Gladstone, R., Greathouse, T.K., Steffl, A., Davis, M.W., Feldman, P.D., McGrath, M.A., Roth, L., Saur, J., Spencer, J.R., Stern, S.A., Pope, S., Freeman, M.A., Persyn, S.C., et al., 2015, The Ultraviolet Spectrograph on the Europa Mission (Europa-UVS): AGU Fall Meeting Abstracts, v. 13, p. P13E–02.
Skidmore, W., and Committee, T.I.S.D.T.& T.S.A., 2015, Thirty Meter Telescope Detailed Science Case: 2015: Research in Astronomy and Astrophysics, v. 15, p. 1945, doi: 10.1088/1674-4527/15/12/001.
Stern, A., and Campins, H., 1996, Chiron and the Centaurs: escapees from the Kuiper belt:
Stern, S.A., Slater, D.C., Scherrer, J., Stone, J., Dirks, G., Versteeg, M., Davis, M., Gladstone, G.R., Parker, J.W., Young, L.A., and Siegmund, O.H.W., 2008, ALICE: The Ultraviolet Imaging Spectrograph Aboard the New Horizons Pluto–Kuiper Belt Mission: Space Science Reviews, v. 140, p. 155, doi: 10.1007/s11214-008-9407-3.
Tegler, S.C., Bauer, J.M., Romanishin, W., and Peixinho, N., 2008, Colors of Centaurs, *in* The Solar System Beyond Neptune, University of Arizona Press, p. 105–114.
Volk, K., and Malhotra, R., 2008, The Scattered Disk as the Source of the Jupiter Family Comets: The Astrophysical Journal, v. 687, p. 714, doi: 10.1086/591839.
West, R.M., 1991, A photometric study of (2060) Chiron and its coma: Astronomy and Astrophysics, v. 241, p. 635–645.
Wierzchos, K., Womack, M., and Sarid, G., 2017, Carbon Monoxide in the Distantly Active Centaur (60558) 174P/Echeclus at 6 au: The Astronomical Journal, v. 153, p. 230, doi:

10.3847/1538-3881/aa689c.

Wong, I., and Brown, M.E., 2016, A Hypothesis for the Color Bimodality of Jupiter Trojans: The Astronomical Journal, v. 152, p. 90, doi: 10.3847/0004-6256/152/4/90.

Highlights

- Flyby concept for 10199 Chariklo, the largest Centaur and smallest ring system
- Opportunity to learn about Kuiper Belt Objects much closer to Earth
- Impactor would provide deepest yet subsurface sampling in the outer Solar System
- Mission concept fits well within NASA New Frontiers Program cost cap
- Mission concept may fit within NASA Discovery Program cost cap